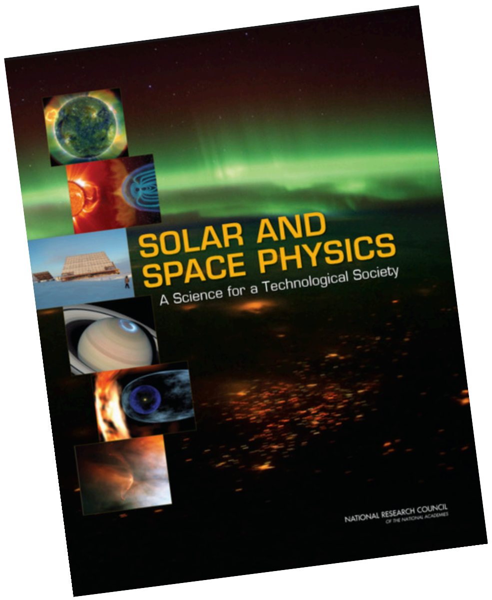
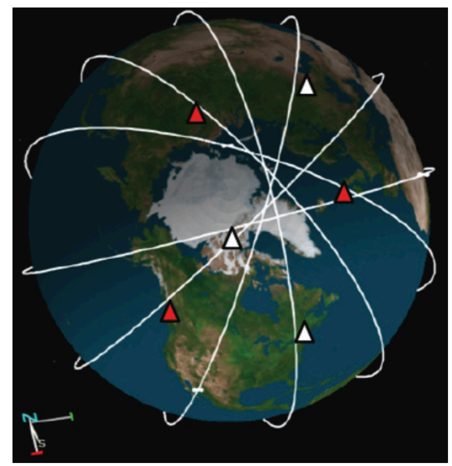
An Overview of the Space Weather Motivation for the "Notional" Geospace Dynamics Constellation Mission

A Strategic Mission Recommended by the National Research Council Heliophysics Decadal Survey as the next major Living With a Star (LWS) Initiative





NASA Space Exploration and Space Weather Workshop

Rob Pfaff
NASA/Goddard Space Flight Center

October 10, 2018

Geospace Dynamics Constellation (GDC)

Overarching Goal

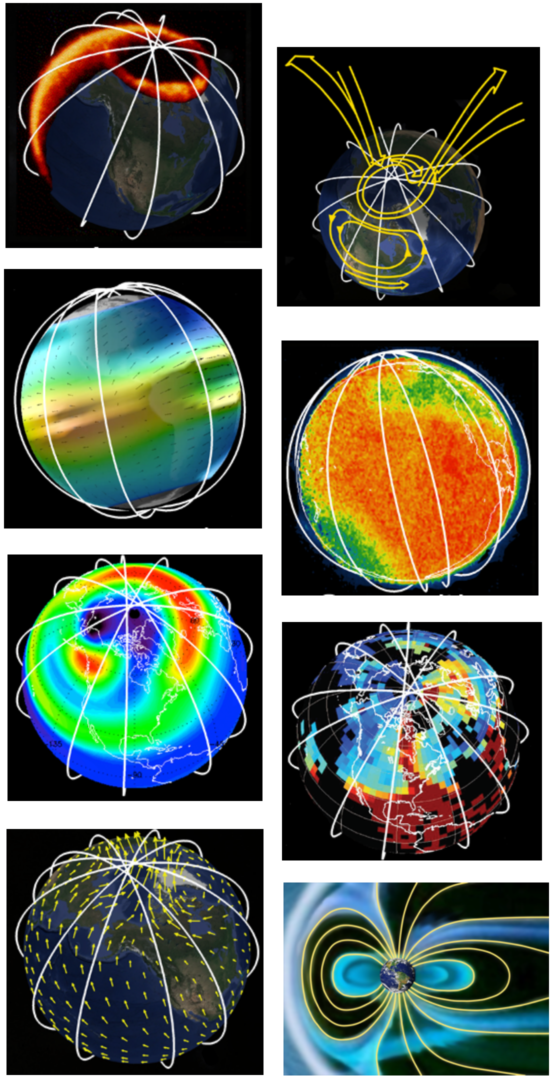
Understand how the ionosphere-thermosphere behaves as a system, connecting to the solar wind and magnetosphere above and the troposphere below.

GDC Addresses

→ **Major Physical Processes/Questions**

→ **Critical I/T Space Weather Problems**

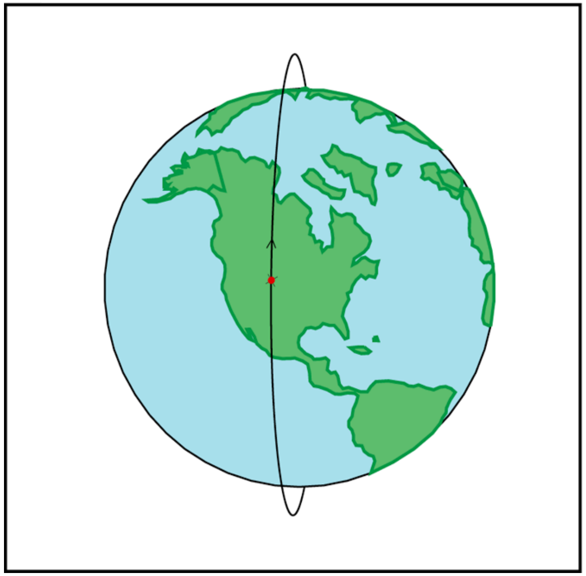
→ **Input for “data-starved” models**



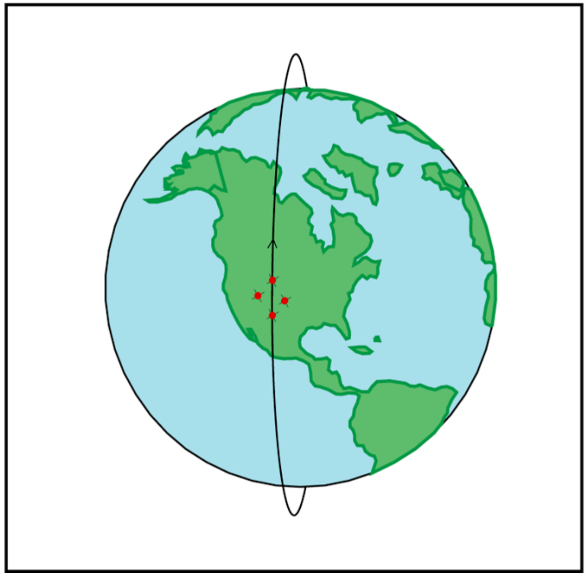
Geospace Dynamics Constellation -- Concept

(Slide from LWS Ionosphere Mappers, ~2000)

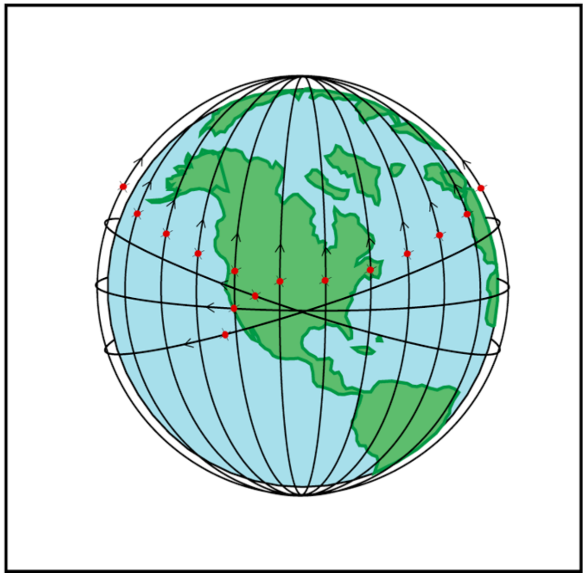
Single Satellite



Cluster of Satellites



Global Network of Satellites



- Event Studies, Exploration
- Provide **Average** Global Conditions
- Example: **Dynamics Explorer-2**

- Event studies resolved in Space,Time
- Reveal cross-scale coupling within ion, neutral gases
- Example: **Global Electrodynamics Connections**

- Global, simultaneous observations at all latitudes, local times
- Uncovers global-scale processes, coupling to other regions
- Reveals structure, large-scale waves along each path
- Example: **Ionosphere Mappers (GDC)**

Geospace Dynamics Constellation -- Science Objectives

Overarching Goal

Understand how the ionosphere-thermosphere behaves as a system, connecting to the solar wind/magnetosphere above and the troposphere below.

GDC Focus -- Critical Science Questions (from Decadal Survey)

1. How does solar wind/magnetospheric energy energize the ionosphere and thermosphere?
2. How does the IT system respond and ultimately modify how the magnetosphere transmits solar wind energy to Earth?
3. How is solar wind energy partitioned into dynamical and chemical effects in the IT system, and what temporal and spatial scales of interaction determine this partitioning?
4. How are these effects modified by the dynamical and energetic variability of the ionosphere-upper atmosphere introduced by atmospheric wave forcing from below?

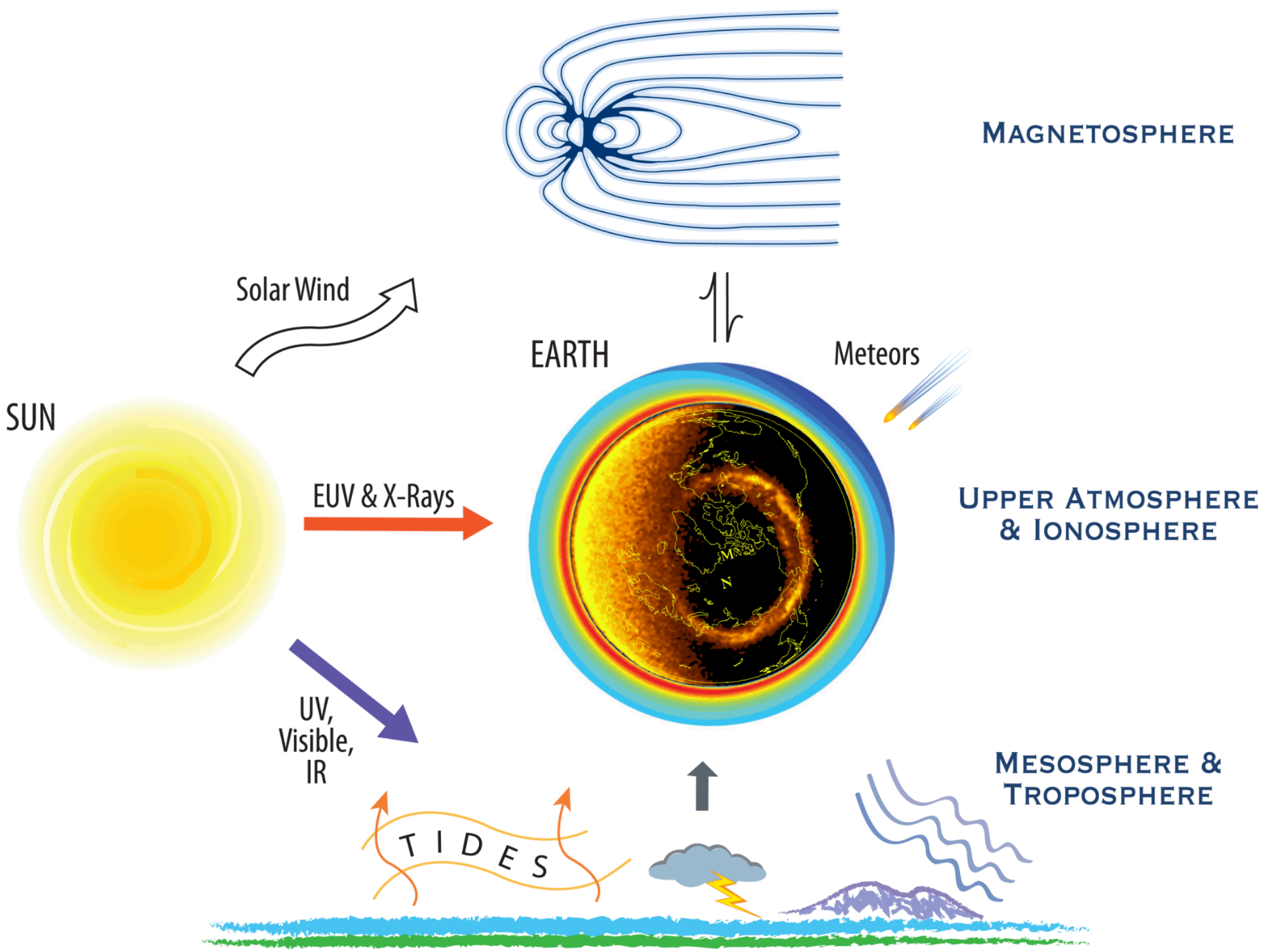
IT coupling and response to Solar Wind Magnetosphere

IT global response to Magnetic Storms

IT response to forcing from below

These Objectives are Discussed Below within Different "Focus Areas"

Pathways of Solar Energy to the Upper Atmosphere and Ionosphere

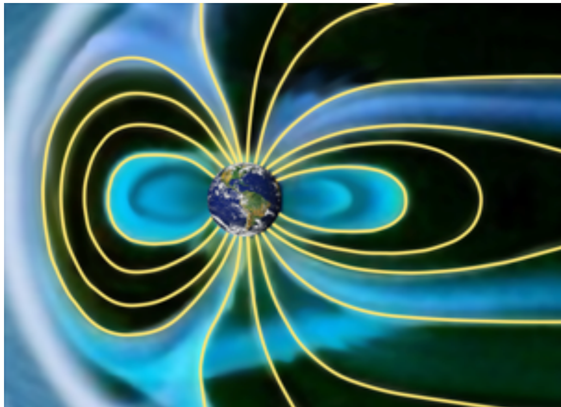


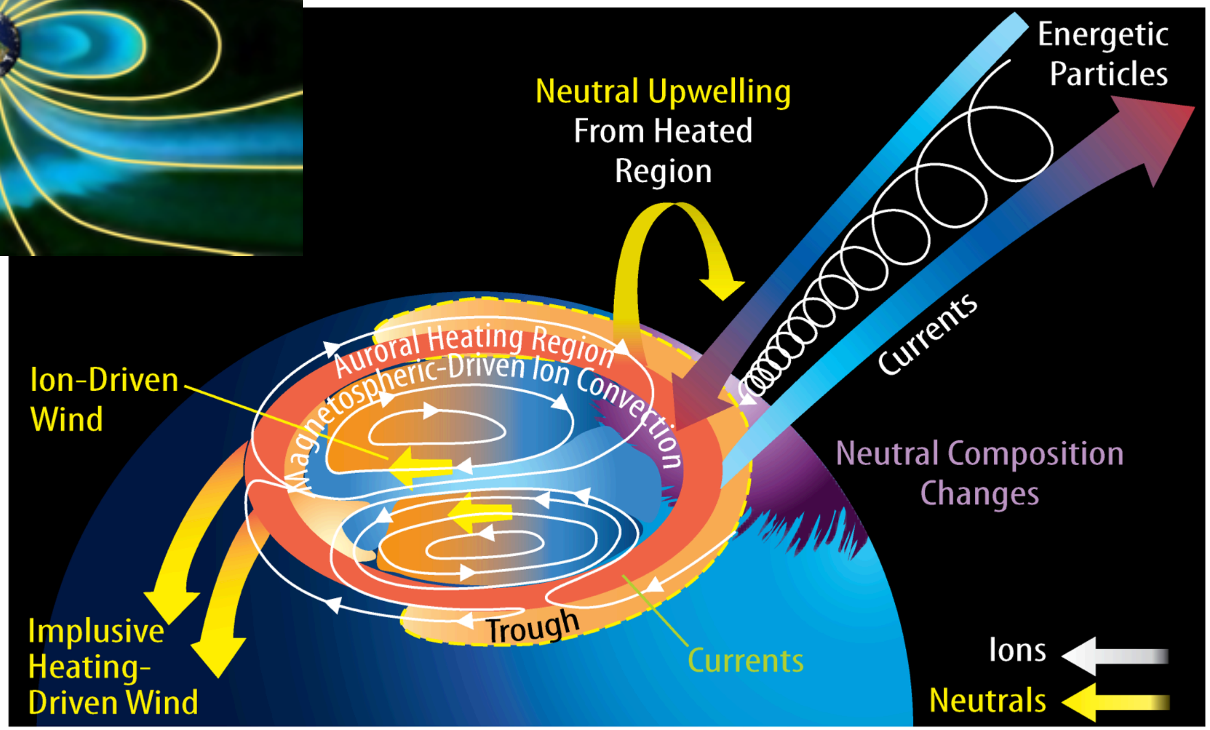
Selected GDC Focus Areas
(Discussed Here)

- → **High Latitude Coupling/Feedback with Magnetosphere**
- → **Global Response of the ITM System to Magnetic Storms**
- → **Ionospheric Irregularities and TIDs at Low/Mid Latitudes**
- → **I/T response to tidal and planetary wave forcing**

Focus Area #1

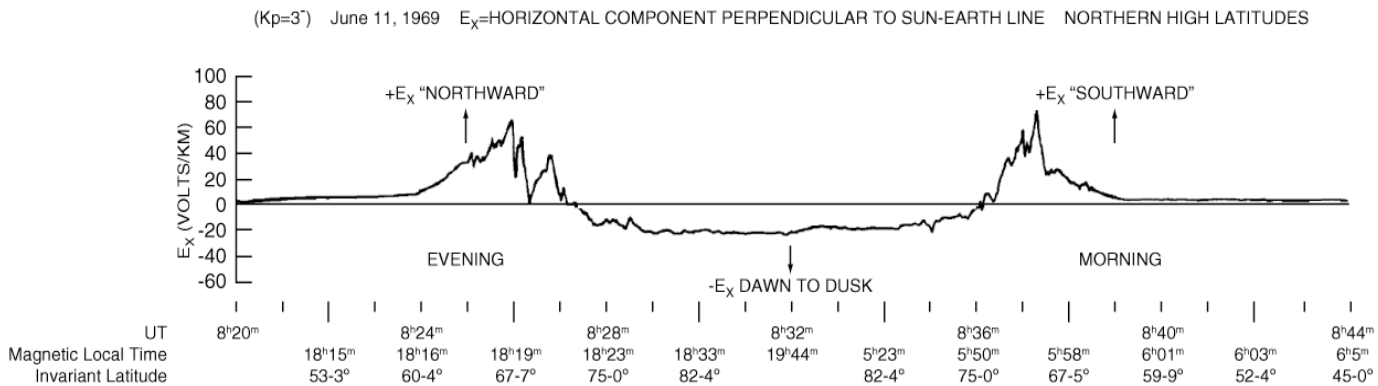
Solar wind/magnetosphere "drives" high latitude Ionosphere/Thermosphere "system" which then feeds back on the magnetosphere!



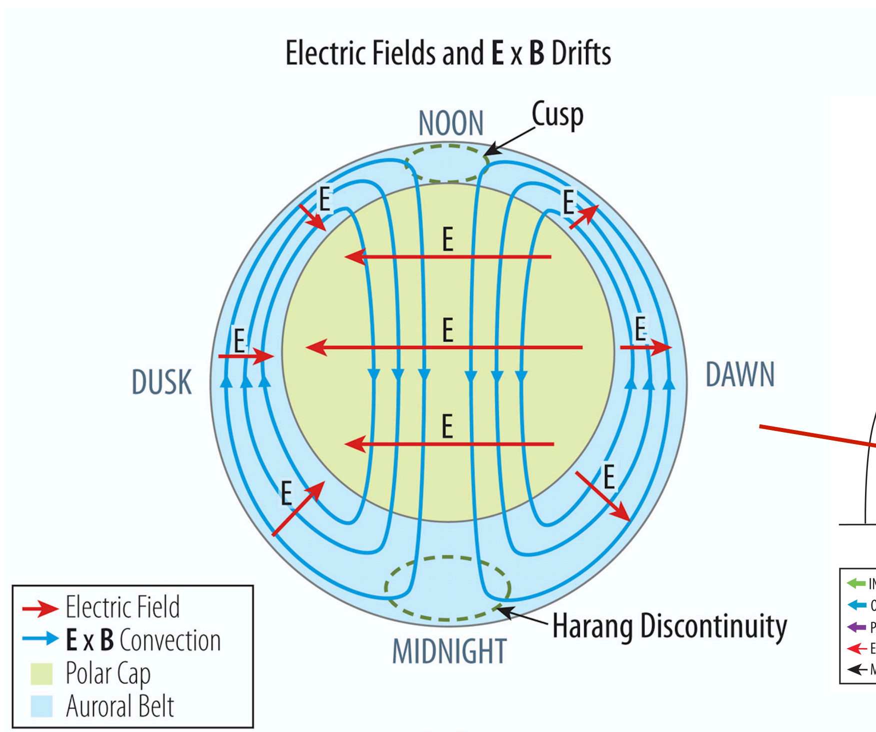


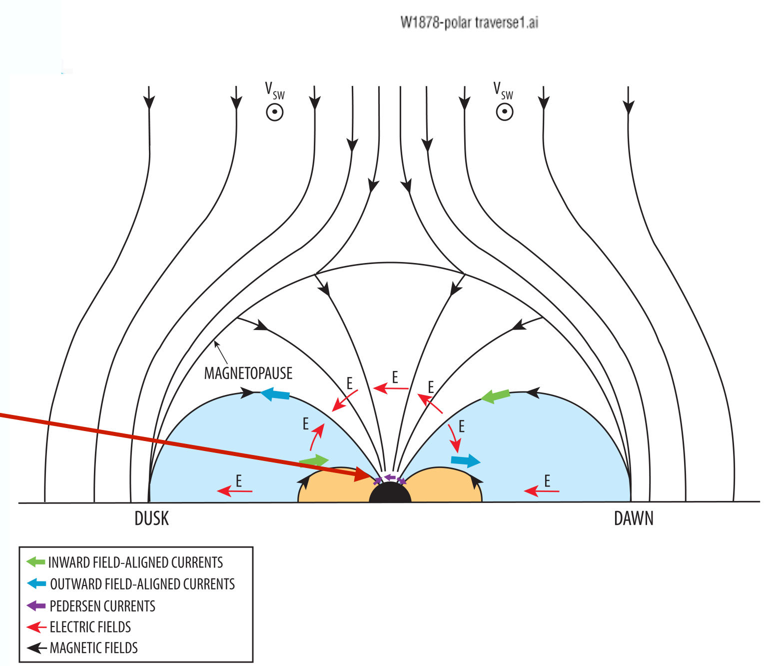
- **GDC** will measure fundamental parameters simultaneously at different LT
- Data addresses host of space weather problems: Geomagnetically induced currents (GIC), neutral density variations and drag, polar cap scintillations, etc.

Single-axis E-field detector reveals fundamental 2-cell convection pattern



Heppner, 1972

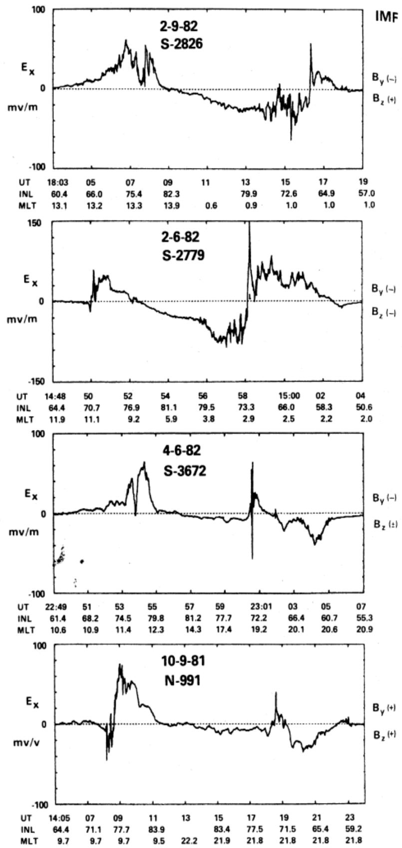


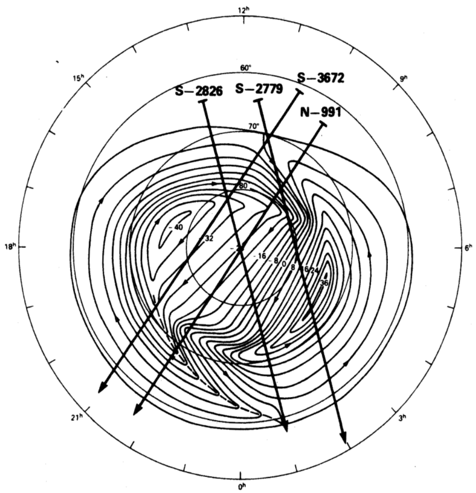


Empirical High Latitude Electric Field Patterns

Derived from N-S E-field Component on Separate DE-2 Passes

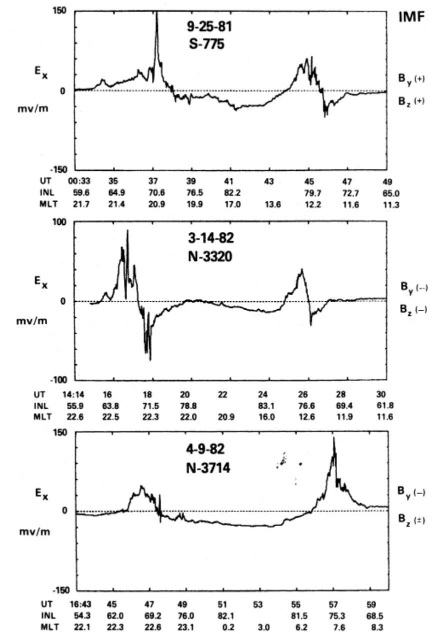
+ IMF By

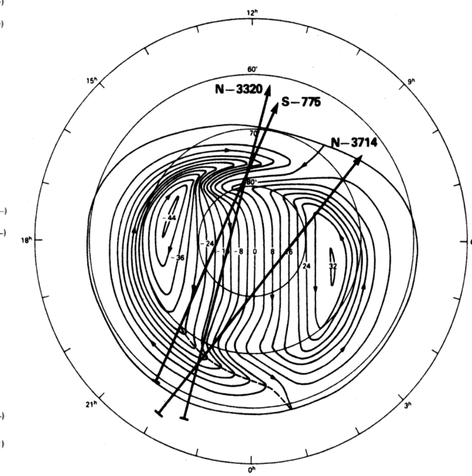




Model BC

– IMF By

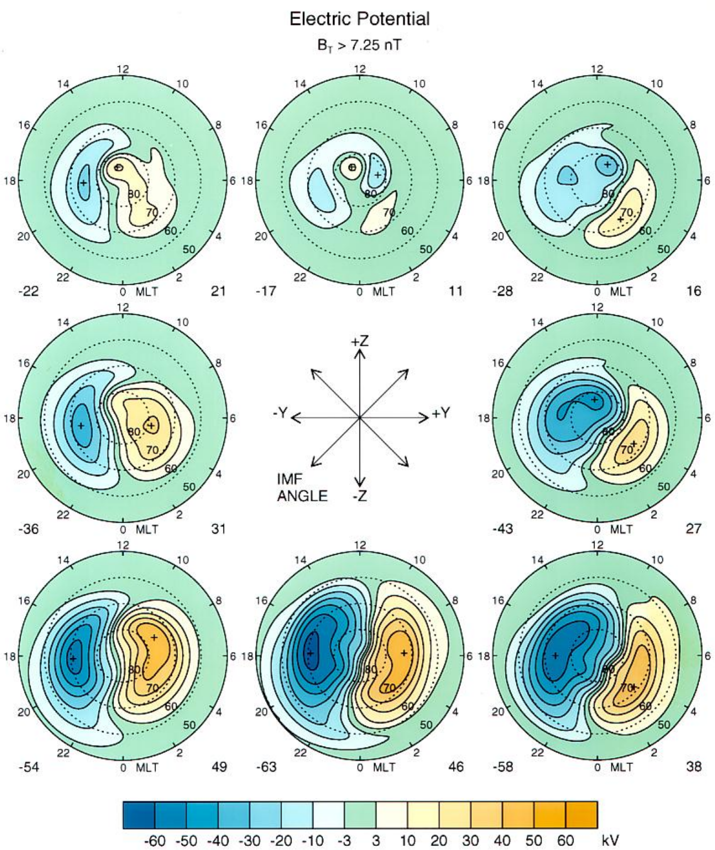




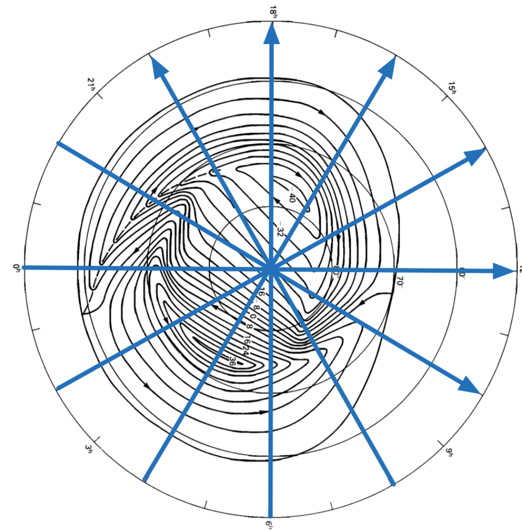
Model A

[Heppner and Maynard, 1987]

GDC provides the next step towards modeling high latitude convection -- simultaneous observations at all local times….

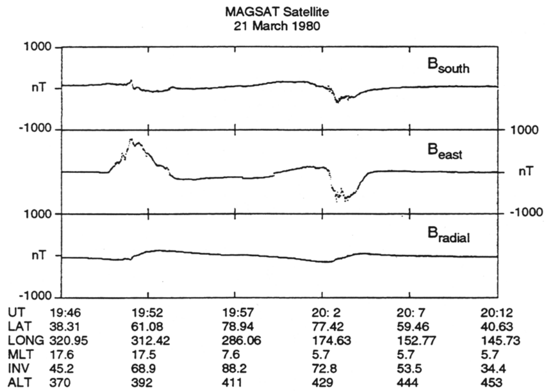


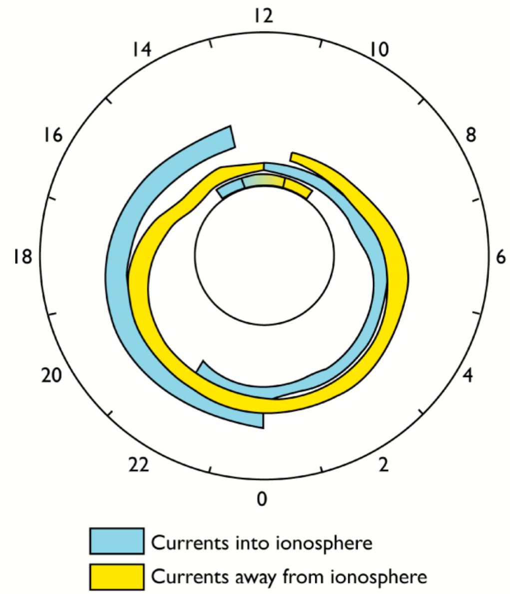
Static Averages binned by IMF



“Dynamic” convection patterns measured by simultaneous, multiple spacecraft

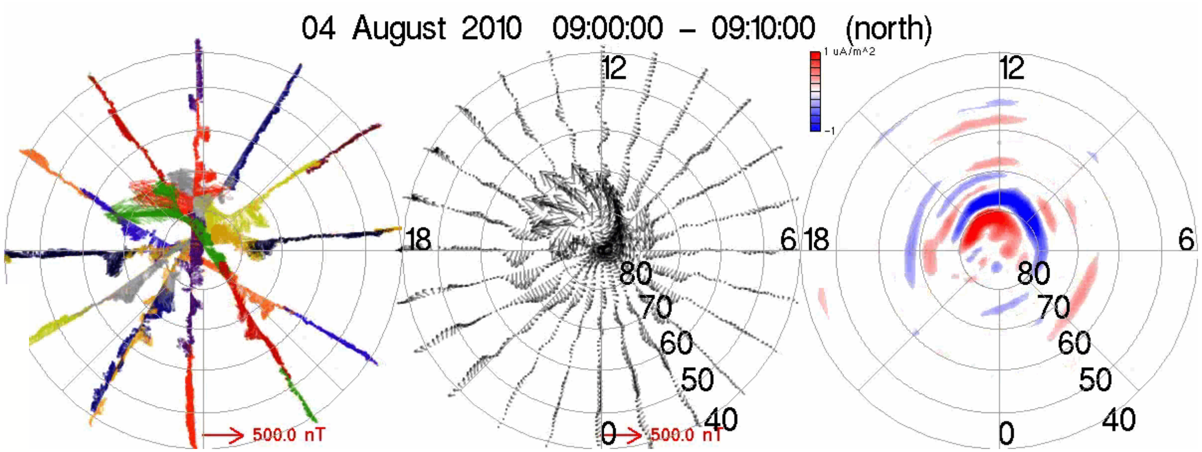
Magnetometer Measurements show Global Measurements of Field Aligned Currents





Iijima and Potemra, 1976

Δ**B** Spherical harmonic fit to Δ**B** Jr = **curl** Δ**B**

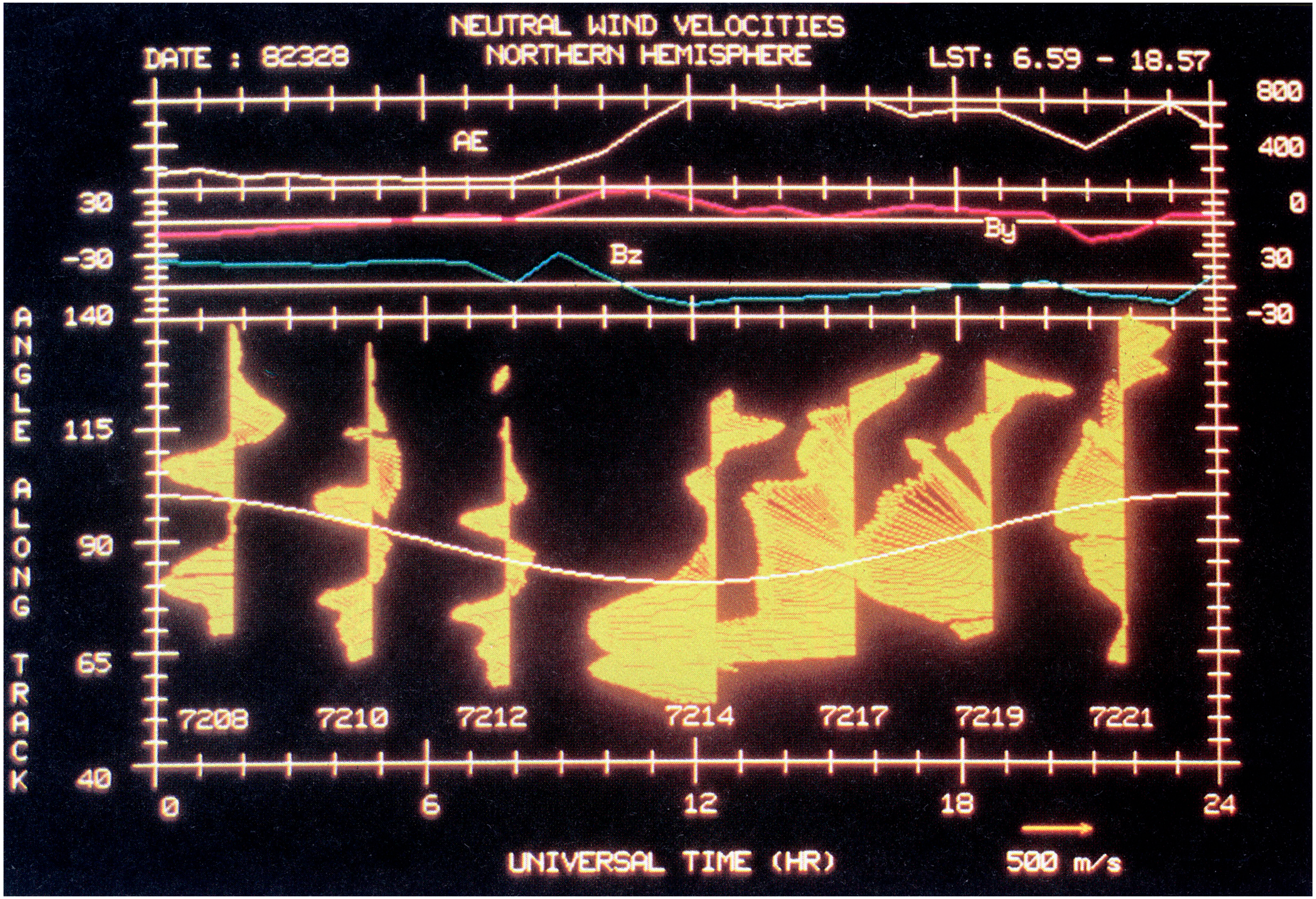


Courtesy B. Anderson

But why not also measure all of the key state variables…
(Neutrals) Un, Nn, Tn, Mn
(Ions) Vi, Ni, T, Mi,
E, **J** (Δ**B**), Energetic Electrons

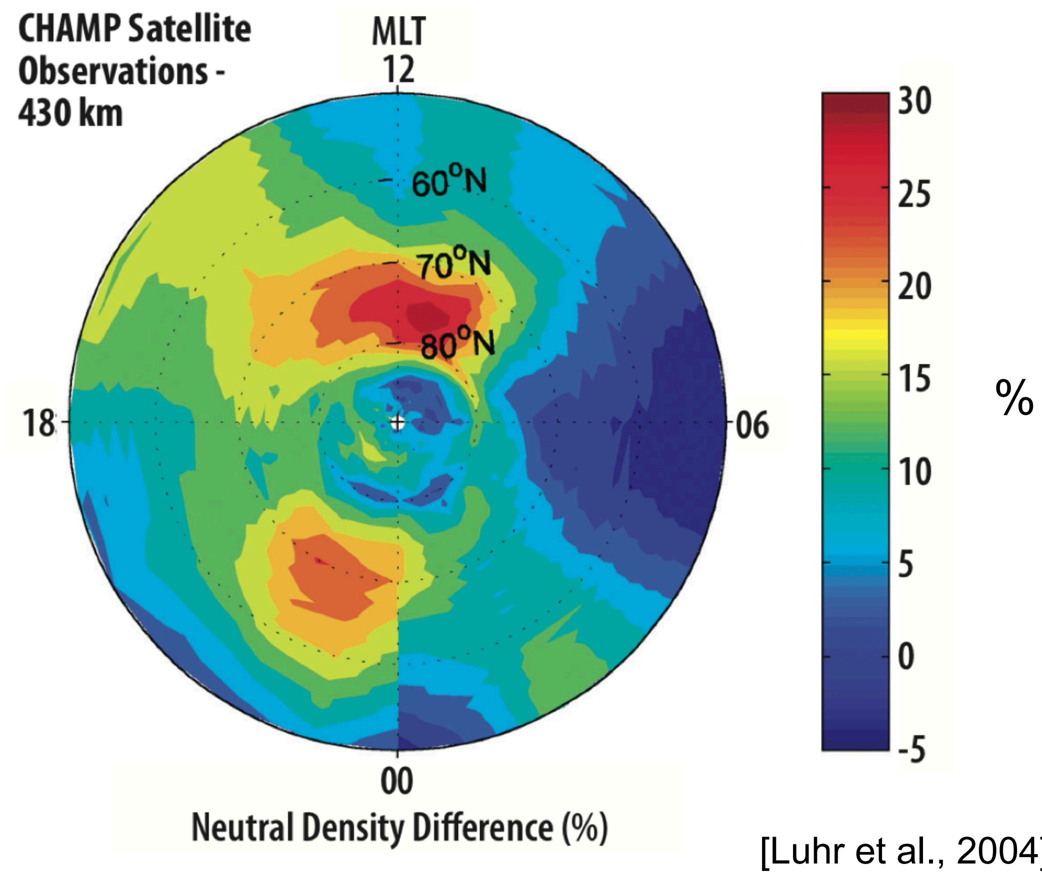
Earth's Upper Atmosphere is thrust into motion by the magnetosphere!

See in particular effects of Geomagnetic Storms!



[Killeen and Roble, 1988]

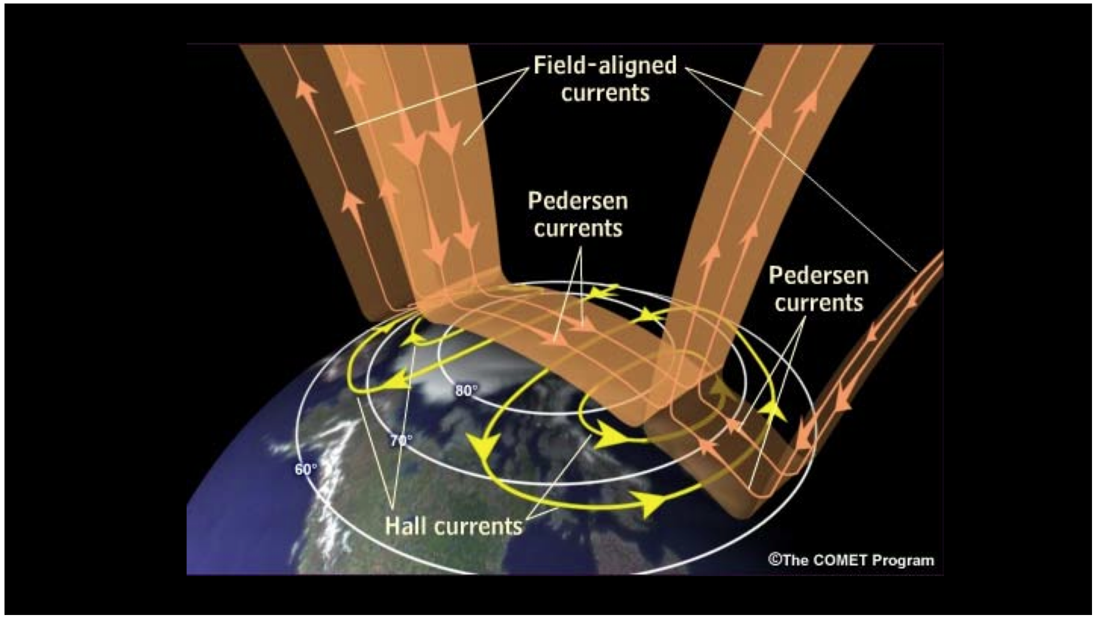
GDC will also reveal **neutral density structures** in the Ionosphere-Thermosphere system and what causes them

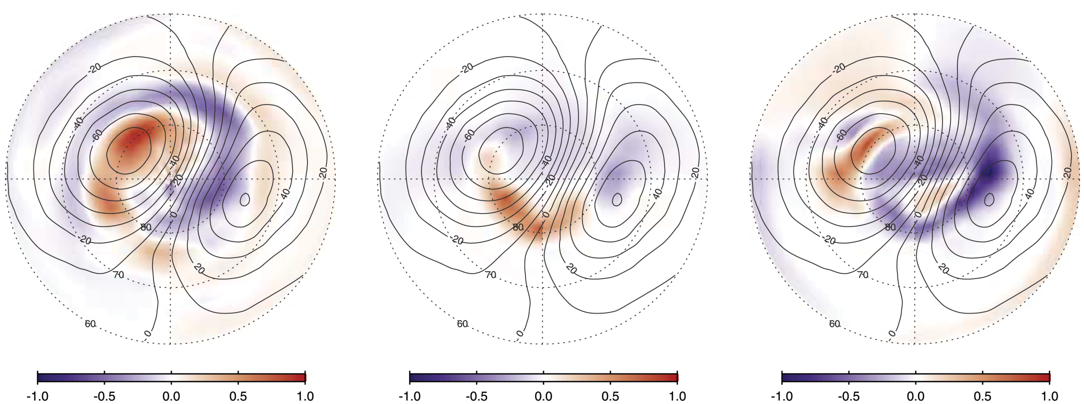


[Luhr et al., 2004]

Neutral density variations at high latitudes are poorly understood --
Thermospheric Upwelling? Driven by Joule Heating?

GDC measurements of currents, electric fields, conductivity (via precipitating energetic electrons), and neutral density will significantly advance our understanding of GIC (Geomagnetically Induced Currents)



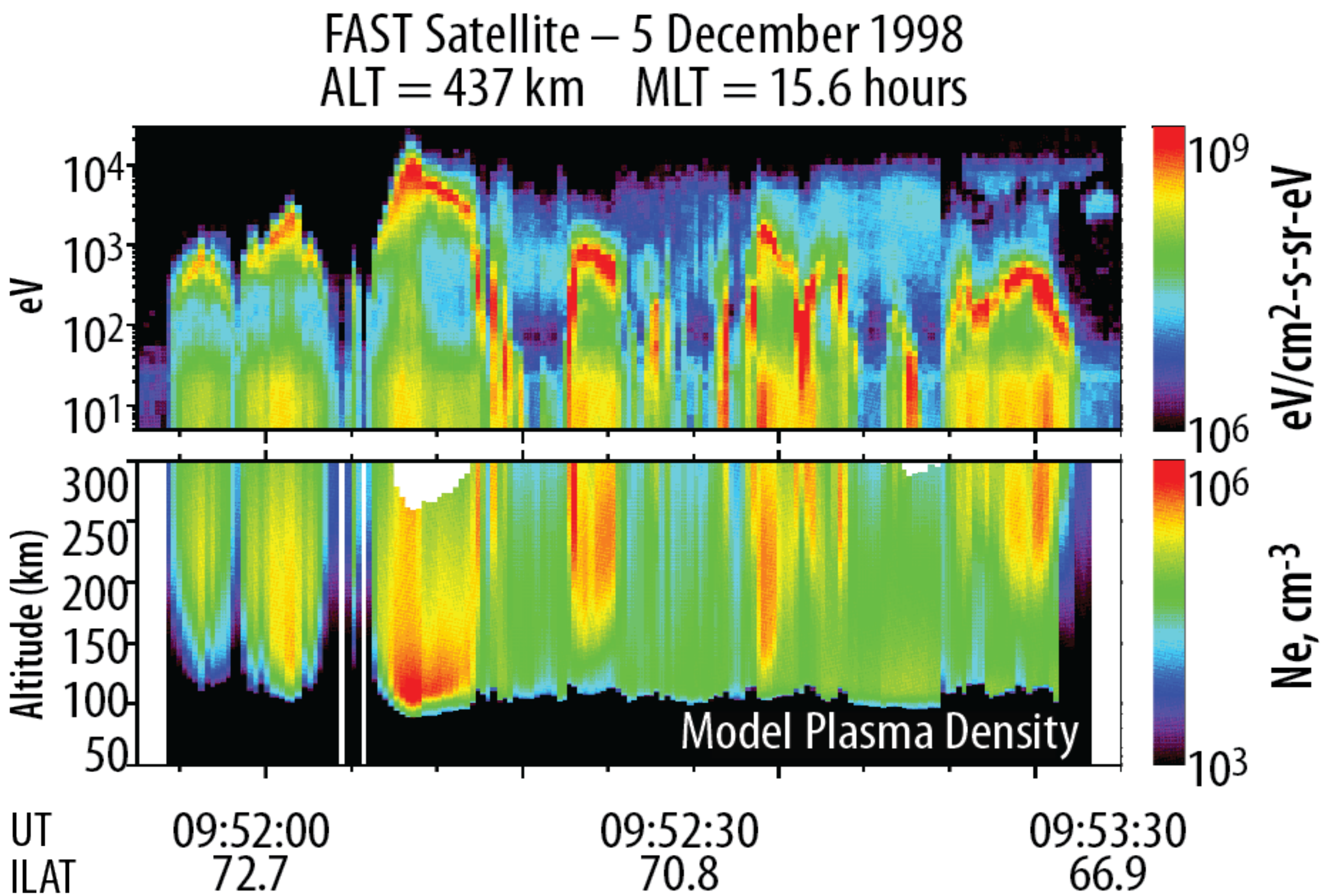


$\nabla\cdot E$, $\mu A/m^2$ $\nabla\Sigma_H$, $\mu A/m^2$ $\nabla\Sigma_P$, $\mu A/m^2$

Model results of currents associated with gradients of electric fields, and Hall and Pedersen Conductivity

[after Lotko, personal communication]

Neutral density determines the creation of thermal plasma and current closure of field-aligned currents due to precipitating electrons

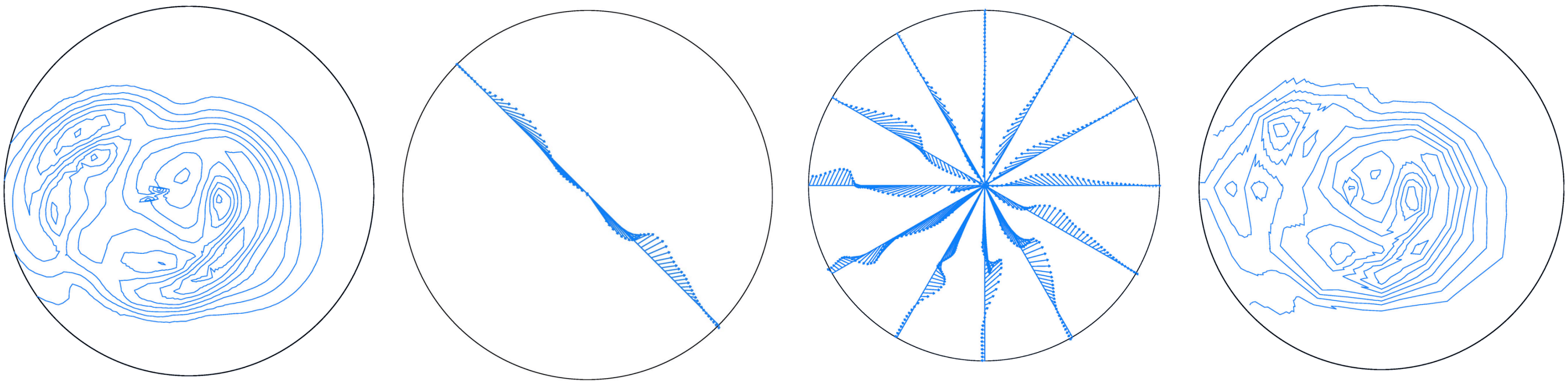


Upper panel: FAST Energetic Electron at 437 km
Lower panel: Model plasma density created by precipitating electrons

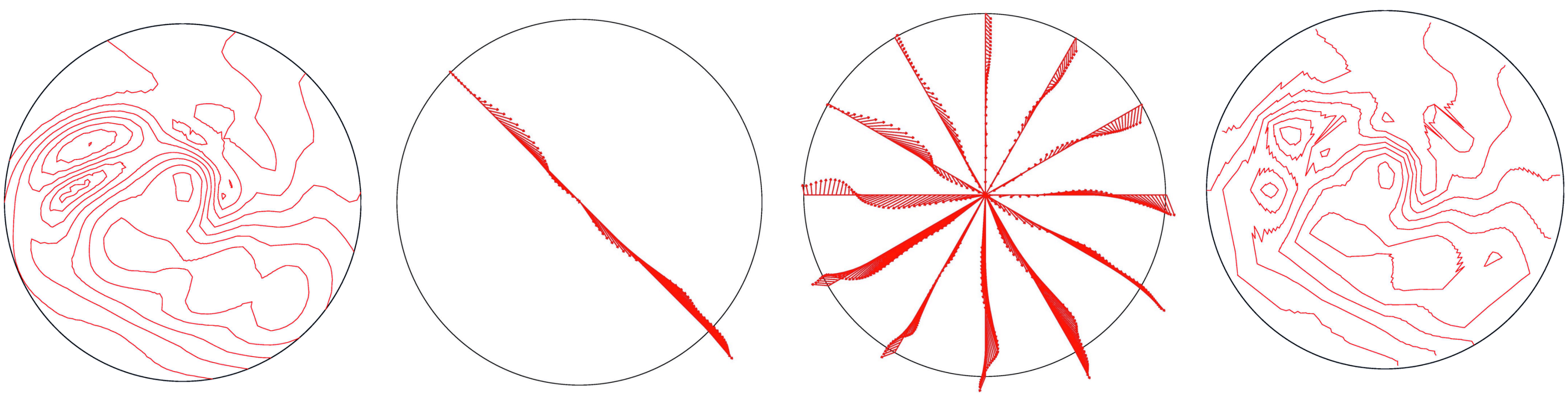
6 satellites cross polar cap as an “armada” in 15 minutes (> 60 deg)

TIEGCM Model | Single Satellite | 6 Satellites | Contours based on measurements from 6 satellites

Ion Drifts



Neutral Winds



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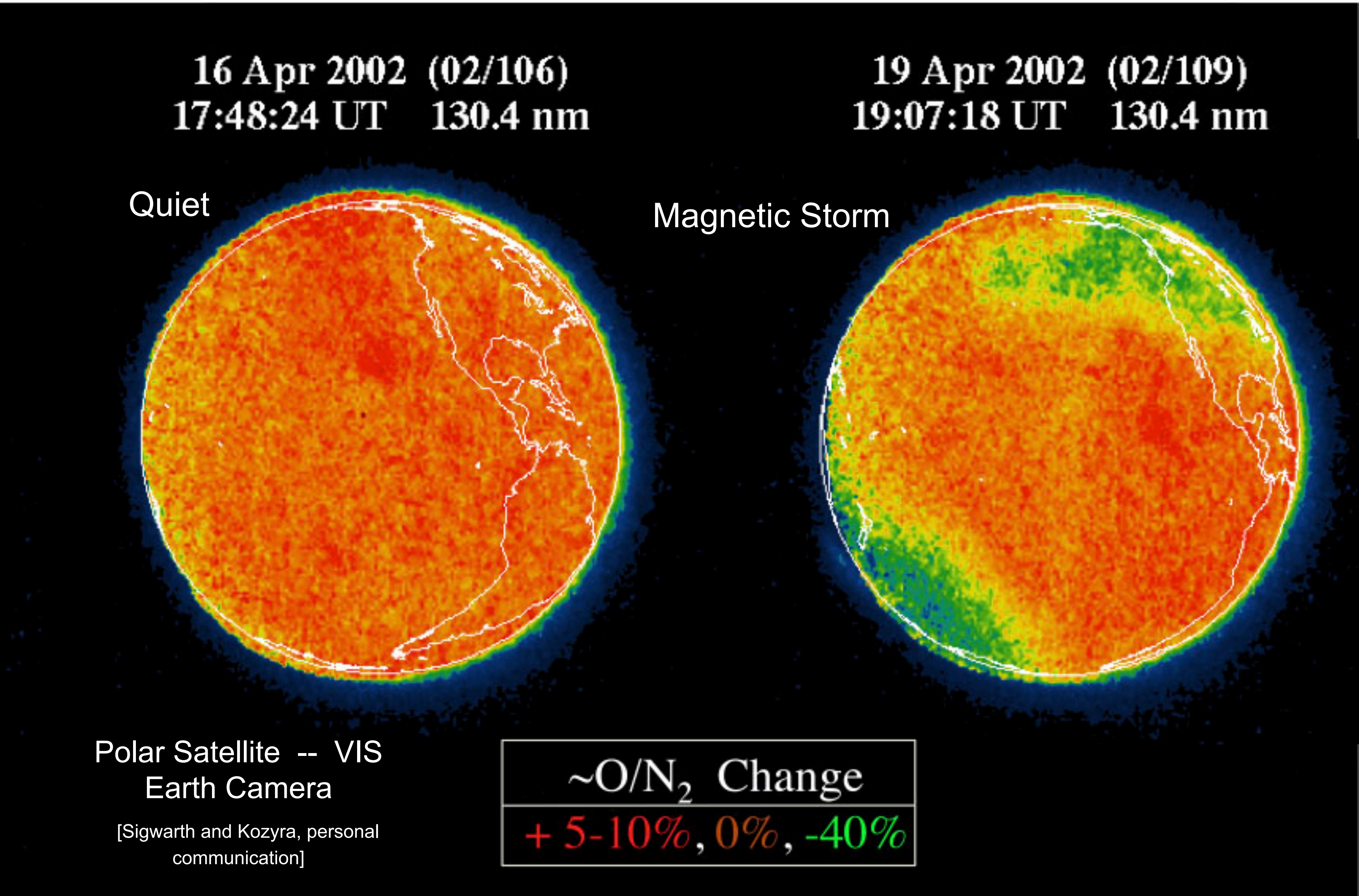
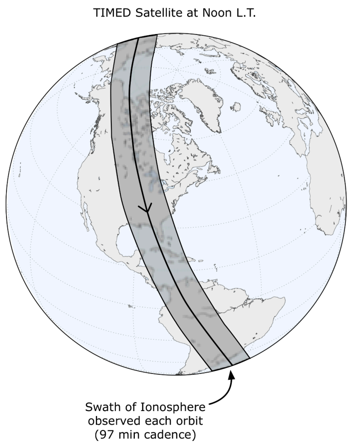
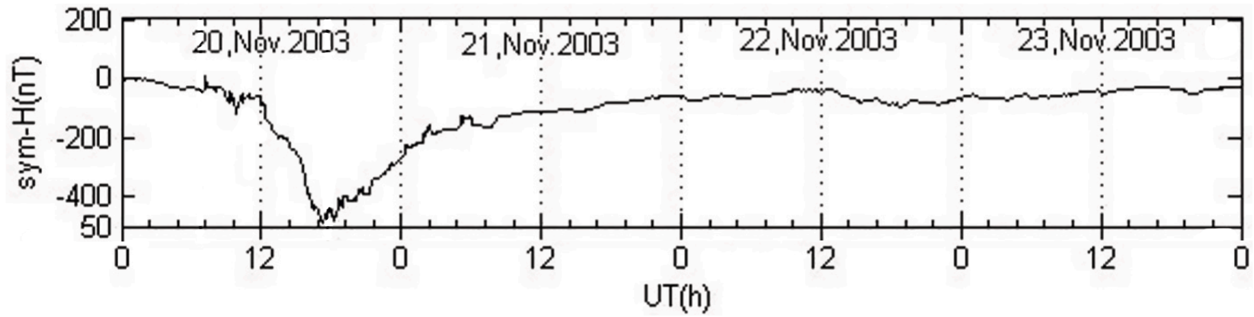
Focus Area #2: Determine the global response to the Ionosphere-Thermosphere system to magnetic activity and storms.



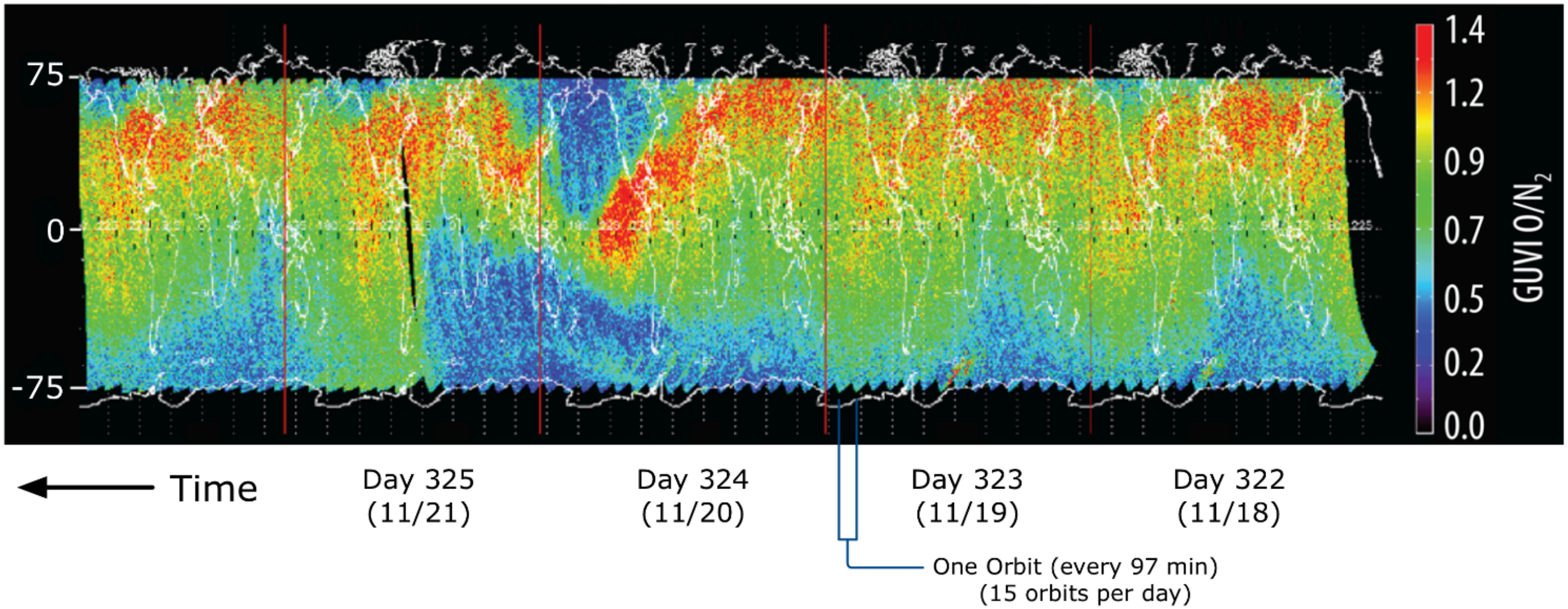




Yang et al., 2003

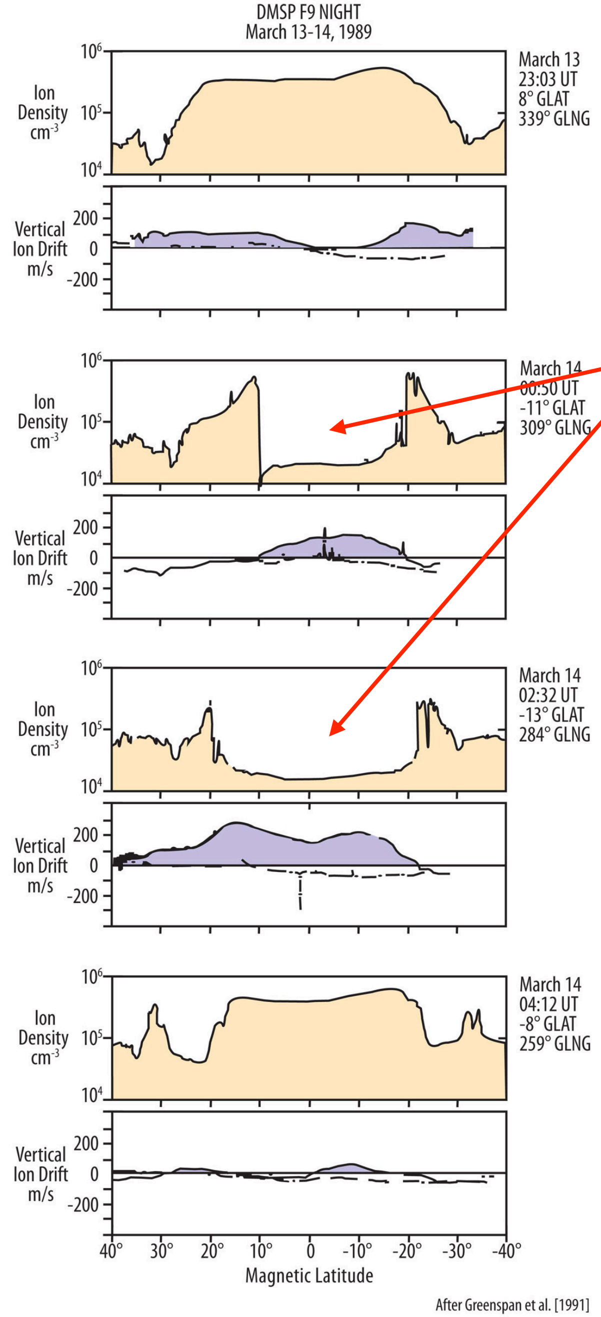
TIMED GUVI Observations near Noon L.T.

Nov. 18 - 22, 2003



[Meier et al., 2005]

4 consecutive DMSP passes (100 minutes apart) near 21:30 L.T. show ionosphere rising above 840 km during magnetic storm!

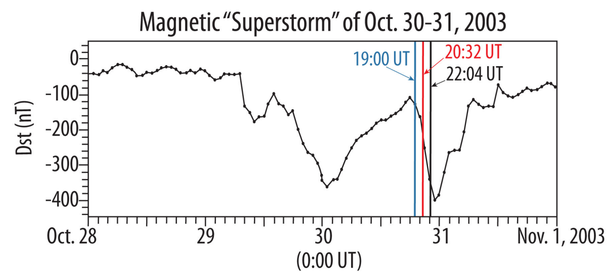


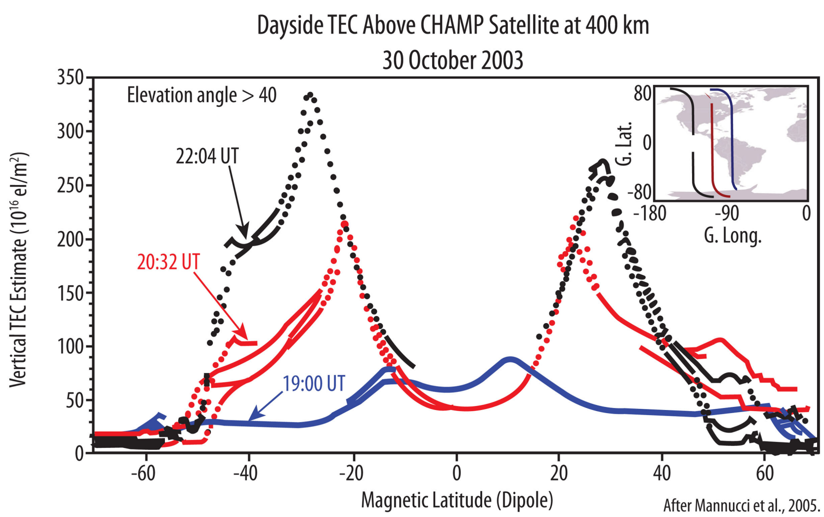
Ionosphere "disappears" at low latitudes

→ Rises above the DMSP satellite at 840km due to intense zonal electric fields

→ What happens at other local times?

GDC will reveal how the mid and low latitude ionosphere responds to magnetic activity and storms, including extreme events.

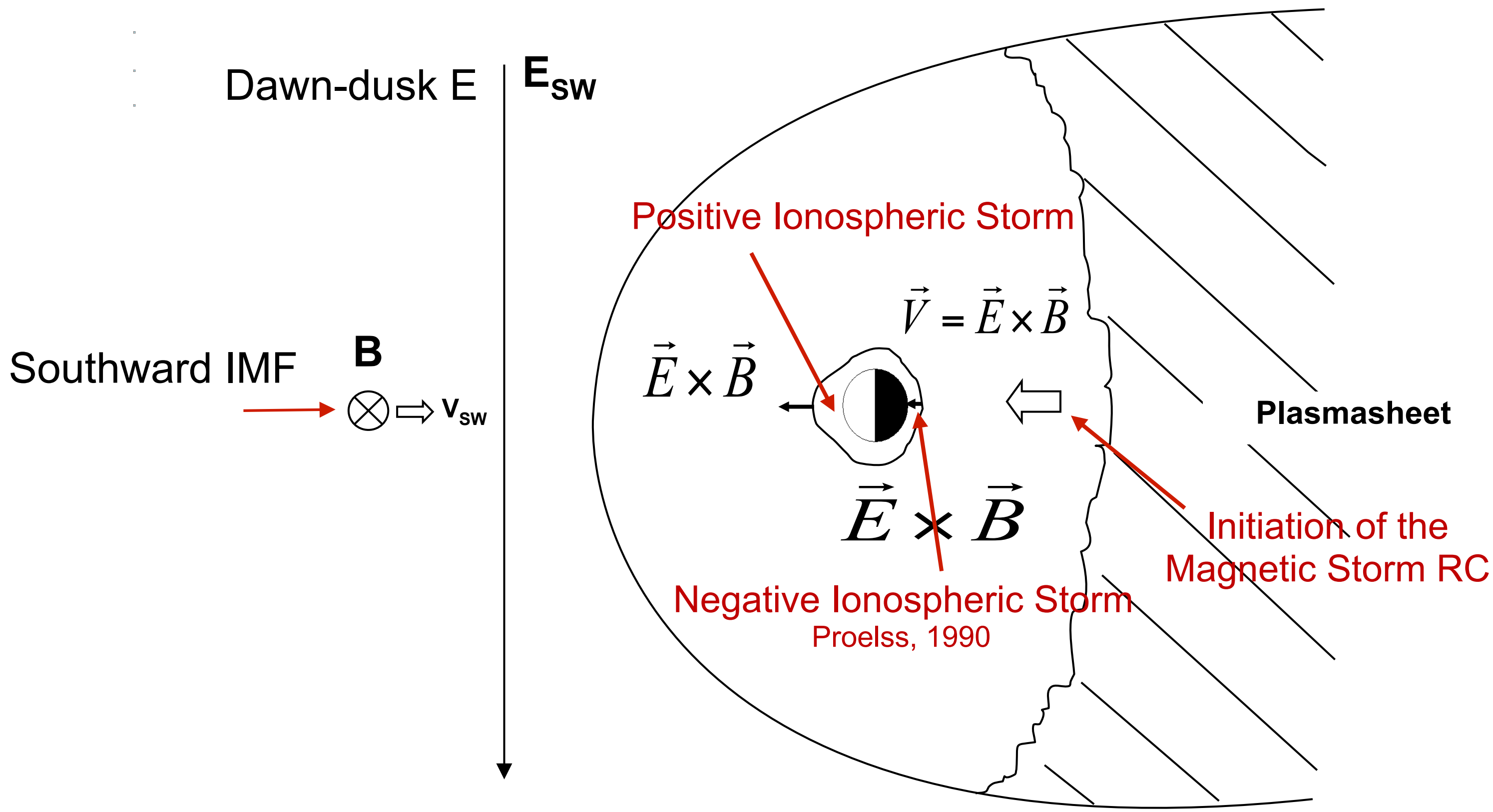




Local times of these orbits -- 12:30 to 13:30 L.T.

TEC measurements (above 400 km) by GPS receiver on CHAMP on 3 successive orbits during magnetic "superstorm" of Oct. 30-31, 2003

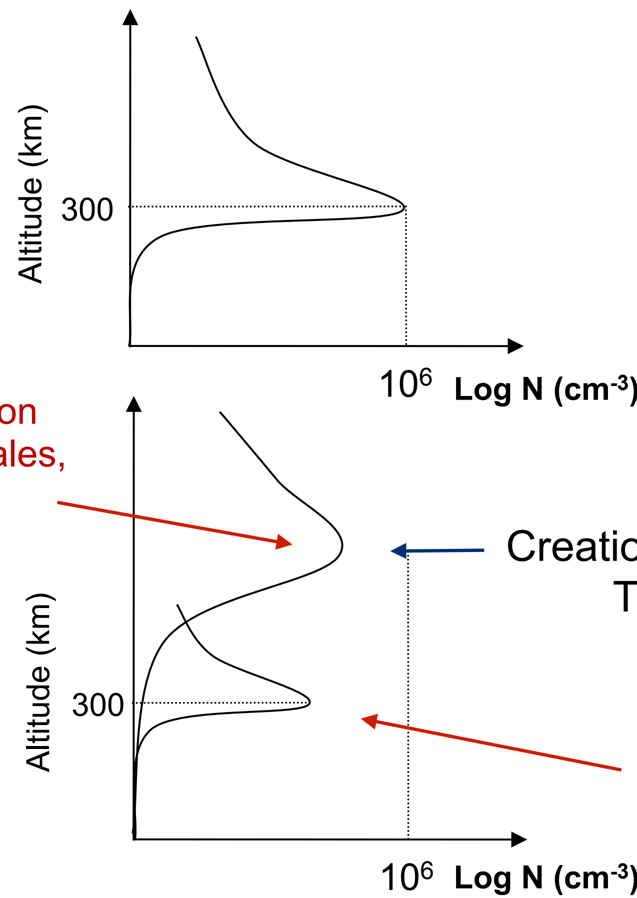
Prompt Penetration Electric Fields(PPEFs) and Their Effects: A Global Scenario



Tsurutani et al., JGR, 2004, 2008

Why Ionospheric Uplift Leads to TEC Enhancements

Quiet



Storm-time

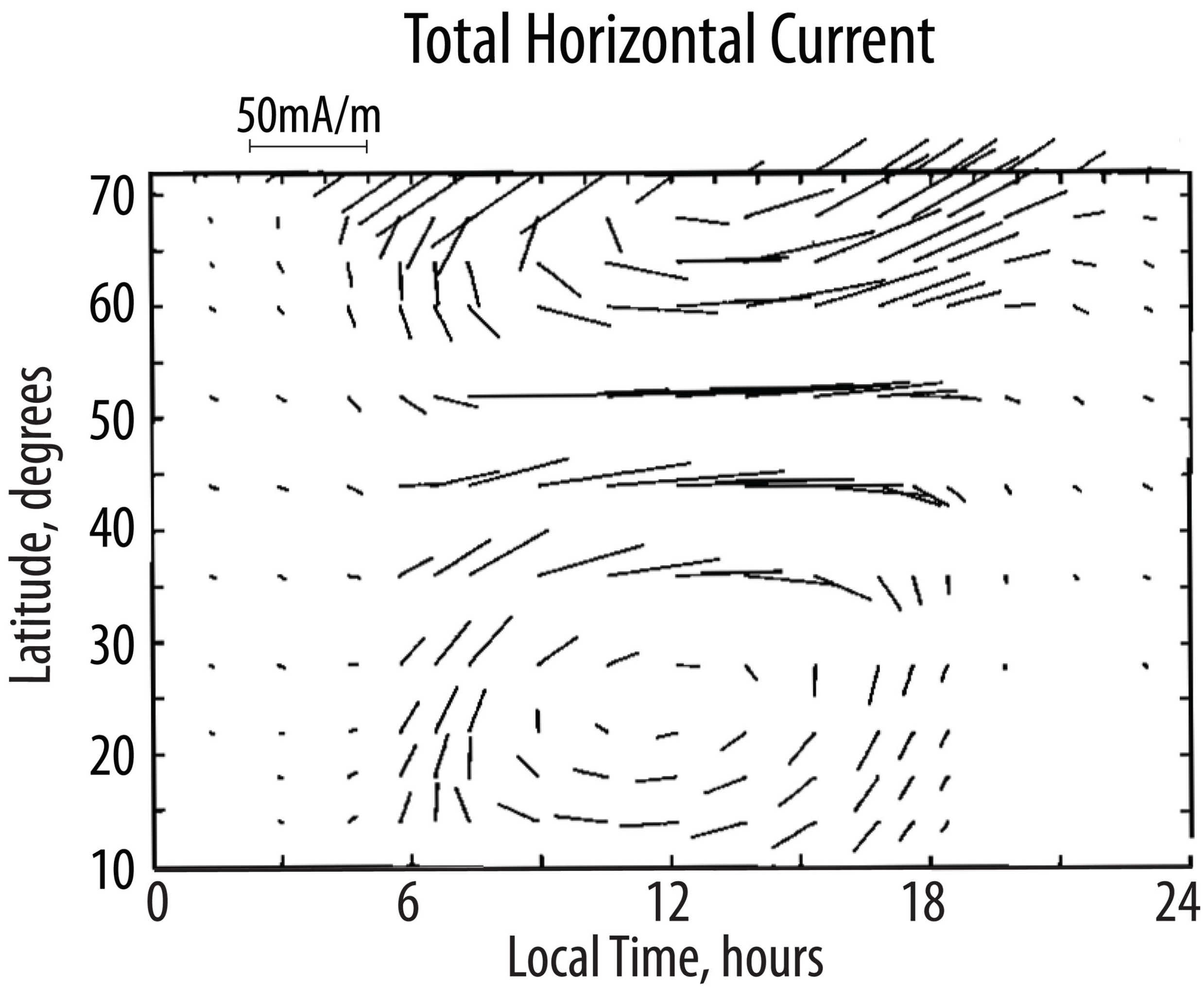
Uplifted plasma moved to region of lower recombination time scales, i.e., longer plasma lifetimes

Creation of a new ionosphere: TEC enhancement

Solar photoionization creates a new ionosphere

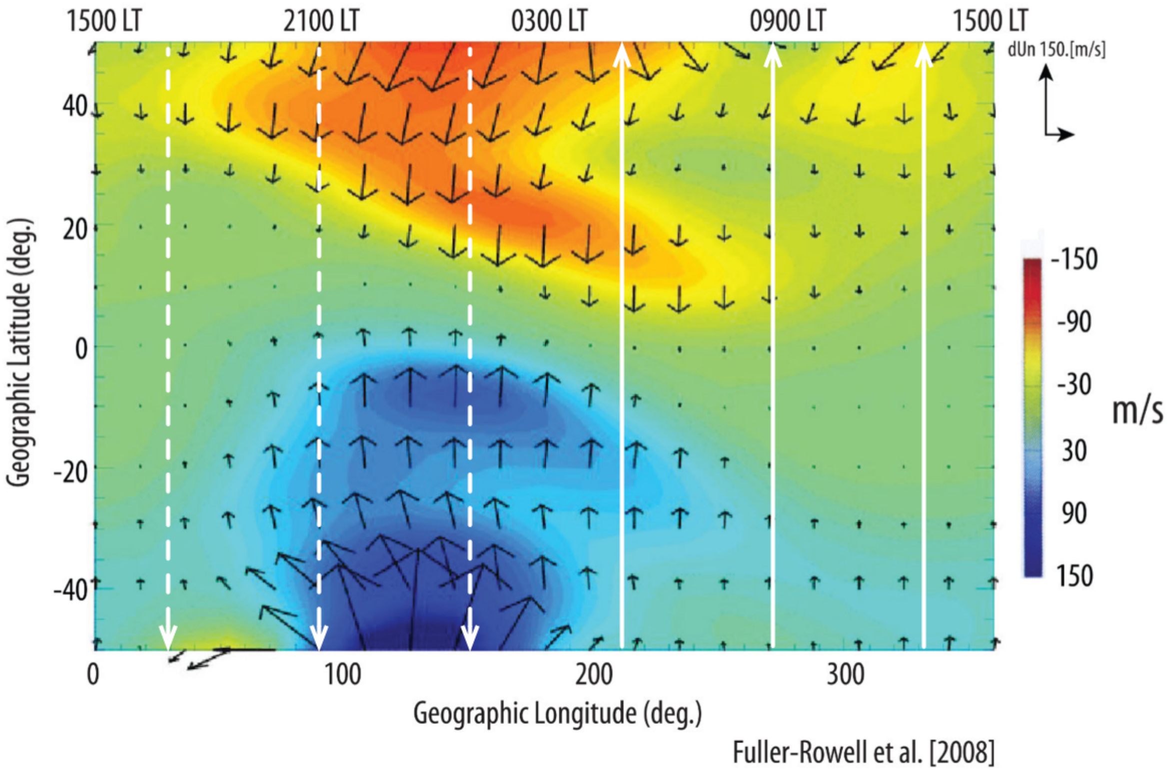
Tsurutani et al., Ann. Geo. [2013]

Currents, Winds and Plasma Velocity (Electric Fields) are Driven in Unknown ways during Magnetic Storms



Blanc and Richmond, 1980

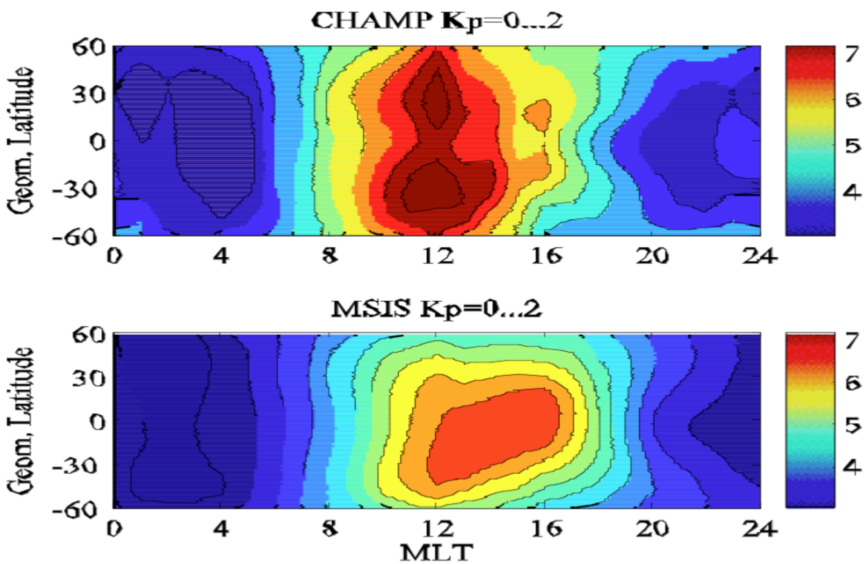
Neutral atmosphere is not only set in motion by the magnetosphere electric fields, but flows to lower latitudes!

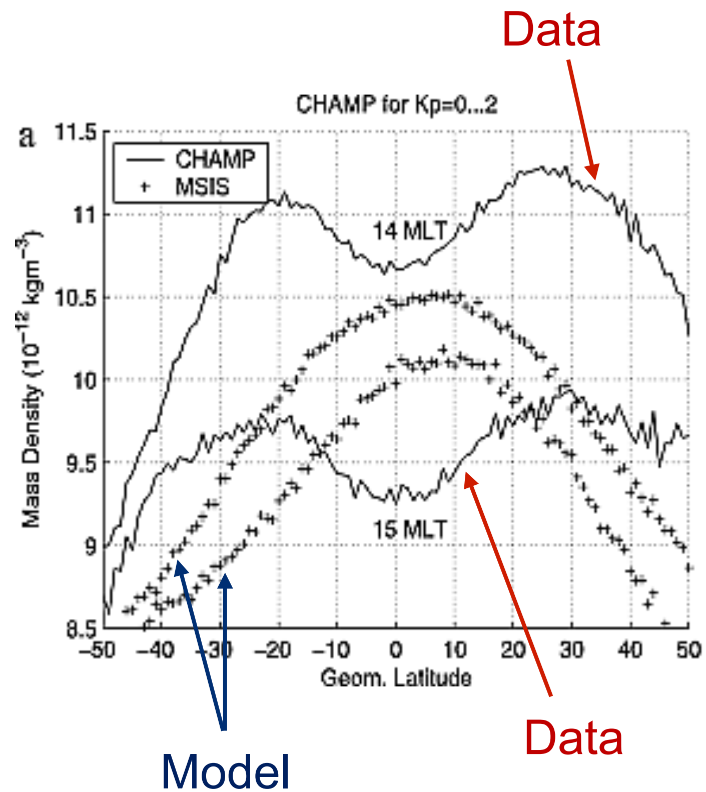


Equatorward winds (Model results at 253 km) driven by auroral heating -- note the strong variations with local time (longitude)

GDC will reveal how the mid and low latitude ionosphere/thermosphere respond to magnetic activity and storms, including extreme events

Comparison of neutral density derived from CHAMP accelerometer and models show major differences





[Luehr et al., 2006]

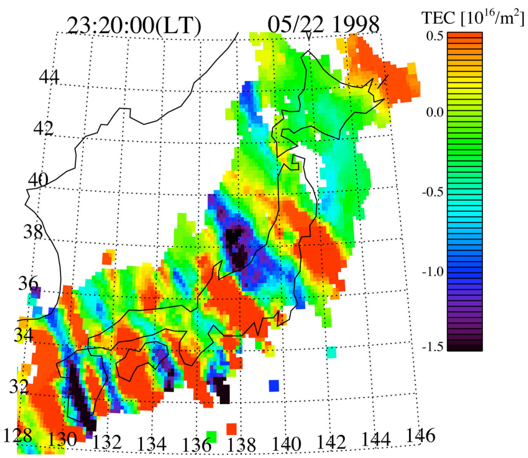
Selected GDC Focus Areas (Discussed Here)

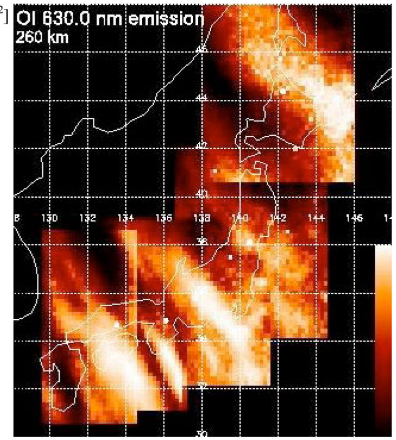
- → High Latitude Coupling/Feedback with Magnetosphere
- → Global Response of the ITM System to Magnetic Storms
- → **Ionospheric Irregularities and TIDs at Low/Mid Latitudes**
- → I/T response to tidal and planetary wave forcing

Focus Area #3: How do neutrals and plasmas interact to produce multi-scale structures in the Ionosphere-Thermosphere system?

Plasma

Neutral





Saito et al. [2001]

Ionosphere-Thermosphere is replete with traveling ionospheric disturbances which represent regional scale ion-neutral coupling

Storm-enhanced plasma density (SED) signatures believed connected to plasmasphere erosion and driven by sub-auroral electric fields from the inner magnetosphere.

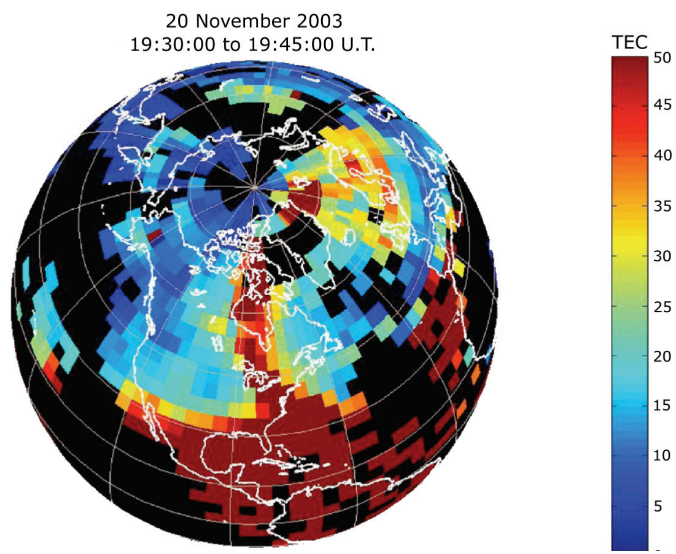
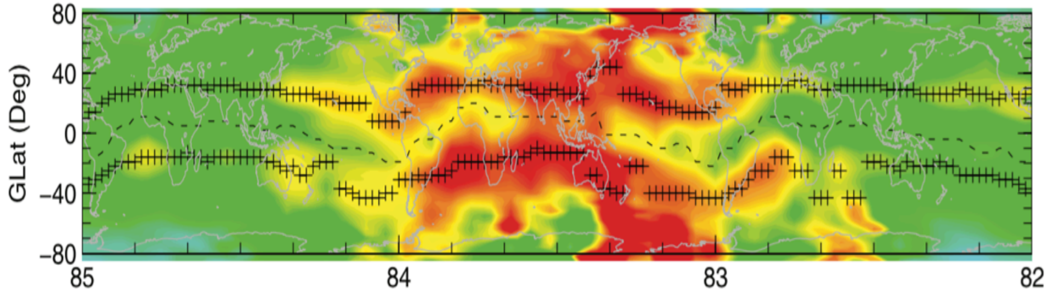


Figure courtesy A. Coster

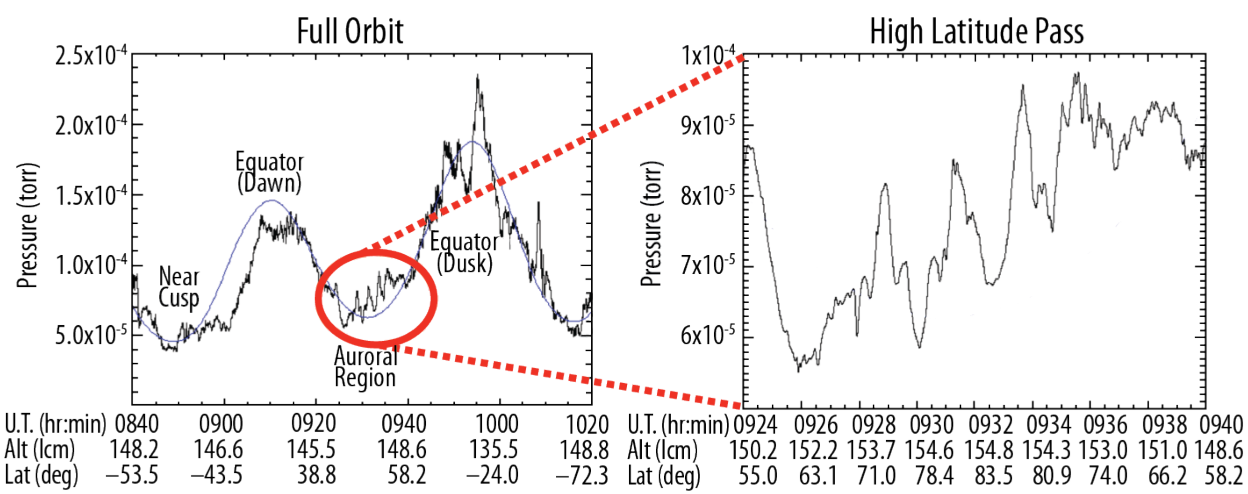
What drives neutral atmospheric structure?

CHAMP Neutral density variations near 400 km



What drives these variations? Are other longitudes/local times affected at the same time?

STREAK Satellite -- 28 June 2006



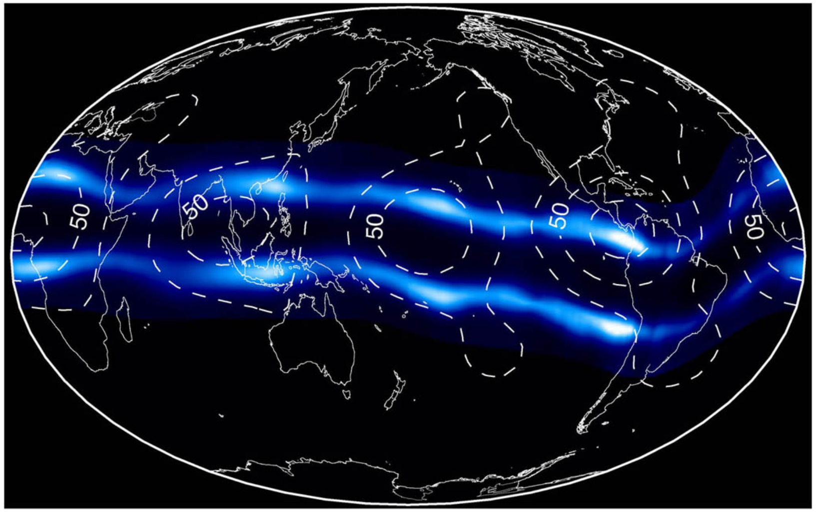
- GDC will reveal the structure in the upper atmosphere and determine its relation to driving energy sources.

Selected GDC Focus Areas
(Discussed Here)

- → High Latitude Coupling/Feedback with Magnetosphere
- → Global Response of the ITM System to Magnetic Storms
- → Ionospheric Irregularities and TIDs at Low/Mid Latitudes
- → **I/T response to tidal and planetary wave forcing**

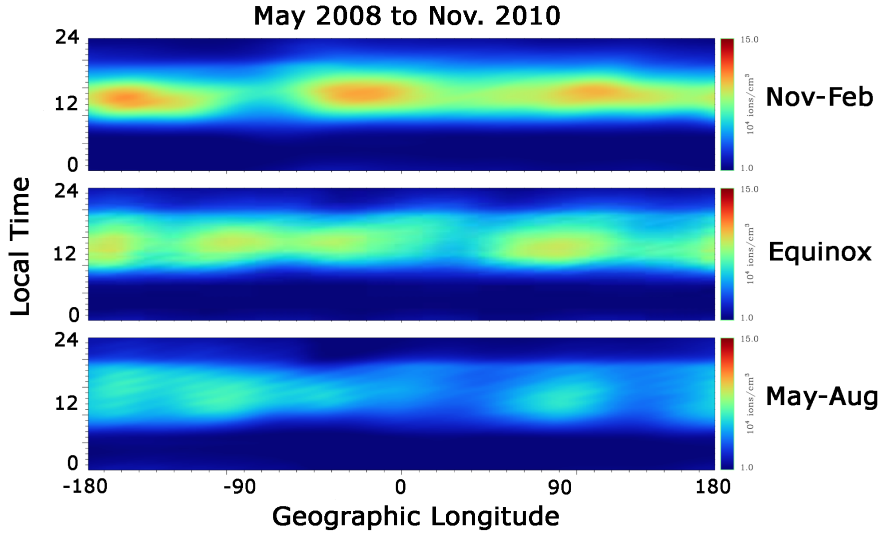
Focus Area #4: How does the Ionosphere/Thermosphere respond to tidal and planetary wave forcing from below?

- Numerous observations have shown the IT system responds strongly to forcing from the lower atmosphere
- IT response depends strongly on both local time and longitude
- Distinguishing simultaneous LT/longitudinal effects requires multi-plane measurements



Tidal effects on plasma density [*Immel et al.*, 2006]

C/NOFS Plasma Density Averages



GD Constellation will address:

How do tropospheric waves/tides contribute to the mean structure, dynamics, and electrodynamics of the thermosphere and ionosphere?

How do neutral winds re-distribute ionospheric plasma, contribute to global electric fields, and drive instabilities?

How does thermosphere respond to during sudden stratospheric warmings?

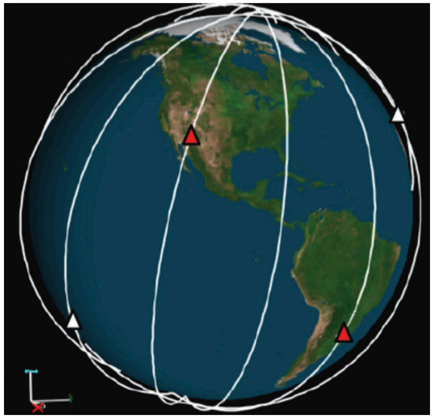
Measurement Approach: Constellation of 6 Satellites Spread in Local Time

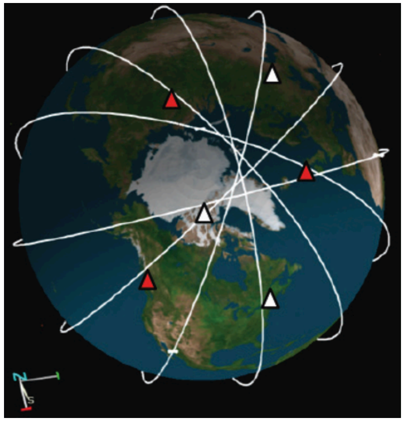
Challenge:

- Global dynamics are not captured by single satellite
- Models must be constrained at more than one plane to make progress

Approach:

- Gather simultaneous, global data using 6 platforms evenly spaced providing 12 local times every orbit
- Satellites in circular orbits (300-450 km)





- Data will be used for global and regional analysis (e.g., high, mid, or latitudes) during quiet/storm conditions
- Using analysis tools (e.g., spherical harmonics), data enable global “maps” of key neutral and plasma gas properties, electrodynamic, and particle measurements, updated periodically (e.g., every 1-5 min)

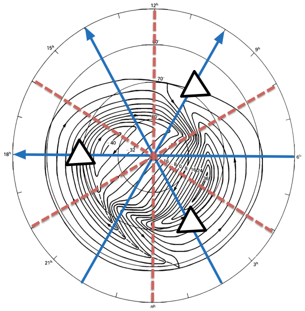
“Formation Flying” Options:

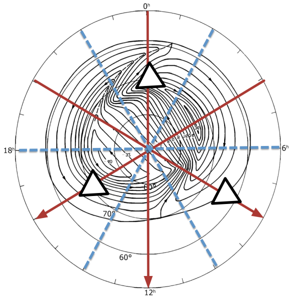
On-board propellant enables:

-- 6 satellites to be flown as an “armada”

-- 3 simultaneous satellites in northern/southern hemispheres

-- other options as well





Three Phases of (Notional) Mission:

Initial Phase: Closely spaced satellites that “fan out” to achieve local time spacing over 9 months-1 year

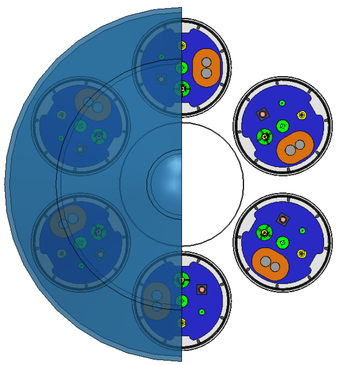
Main Phase: Circular orbits between 300 - 450 km, re-boosted periodically

→ ***Nominal Main Phase: 5 Years, with fuel for 10 years***

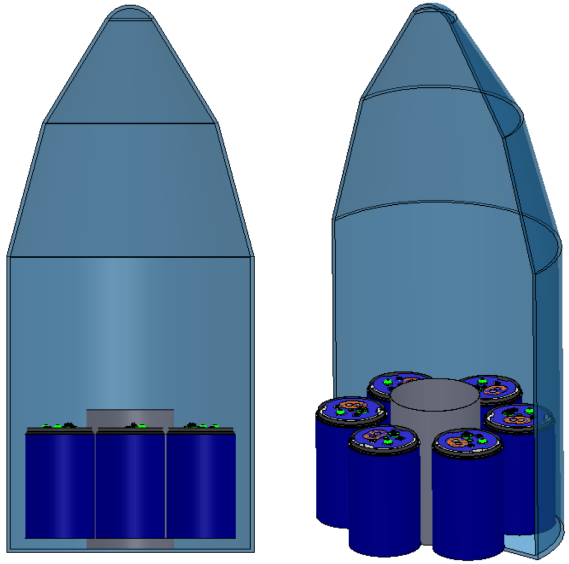
Final Phase ~ 3-6 months: Synchronized re-entry, with coordinated measurements gathered below 300 km.

Several Launch Vehicle Options are Feasible

Shown below is Taurus II (enhanced) launch option provide by Aerospace Corp.



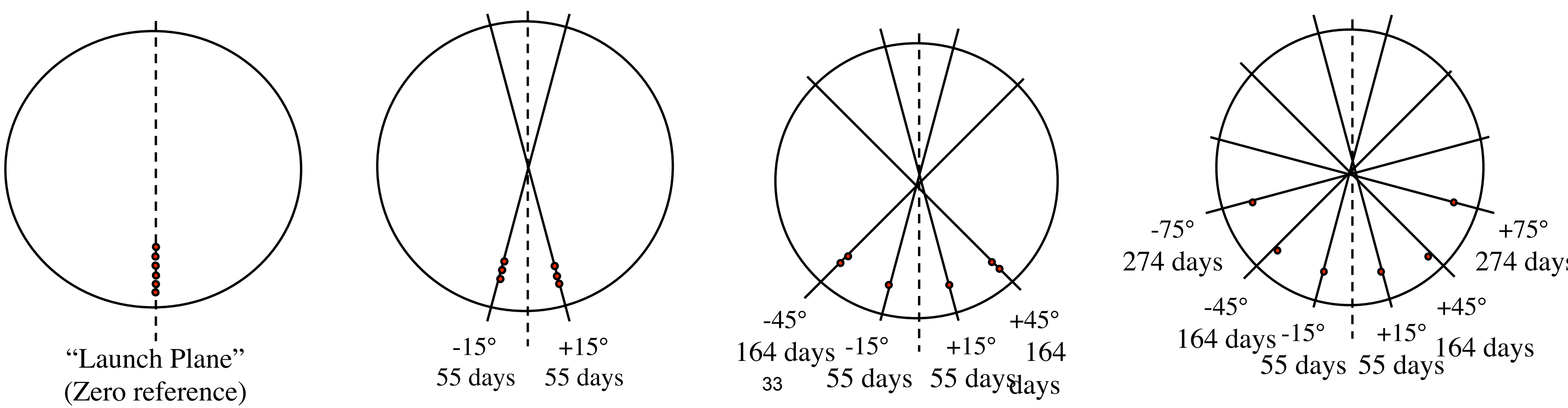
3.9 m (155 in) diameter
Payload Faring



- All instrument (level 1 and 2) are accommodated by this configuration.
- Volume available in Taurus II allows for multiple stowage configurations. Another option would be two levels of 3 spacecraft around the central dispenser.
- Satellites initially in “pearls on string” elliptical orbits (450 by 2000 km at 80° incl.) to achieve local time spacing in 9 mo-1year

→ Provides exciting higher altitude measurements

Ionospheric Mappers -- GSFC IMDC Study -- Satellites Spaced in 9 months



GDC Measurements -- General Approach

-- Each GDC Satellite will gather accurate, comprehensive measurements of all of the state parameters that define key processes in the I-T system, including energy/momentum input from above and below.

-- Identical satellites in circular, polar orbits near 350 km altitude spaced in local time

-- Large propellant tanks to achieve separation, maintain low altitude orbits, station keeping, ensure significant mission lifetime.

GDC Satellite Measurements:

– **Gas properties** (Neutral, plasma: densities, winds/drifts, temperatures, composition)
– **Fields properties** (Electric and Magnetic Fields, Currents)
– **Energetic Particles** (electrons, ions, eV to tens of keV)

→ "Remote sensing" instruments such as local sounders, Fabry-Perot interferometers, as well as imagers on other platforms, also to be considered

Key Components of the GDC Mission Beyond Satellites:

-- **Ground-based component** integral part of mission

-- **Strong theory and modeling** important for mission definition and data analysis

-- **Open data policy** with **robust data analysis funding** for entire community

Geospace Dynamics Constellation will provide Major Improvements for Space Weather Knowledge, Nowcasting, and Forecasting

- → Understanding/predictions of disruptions in navigation and communication signals
- → Major improvements in satellite drag models
- → Unprecedented knowledge of geomagnetically-induced currents in electrical power grids.

GDC has a natural, integrated Global Modeling component

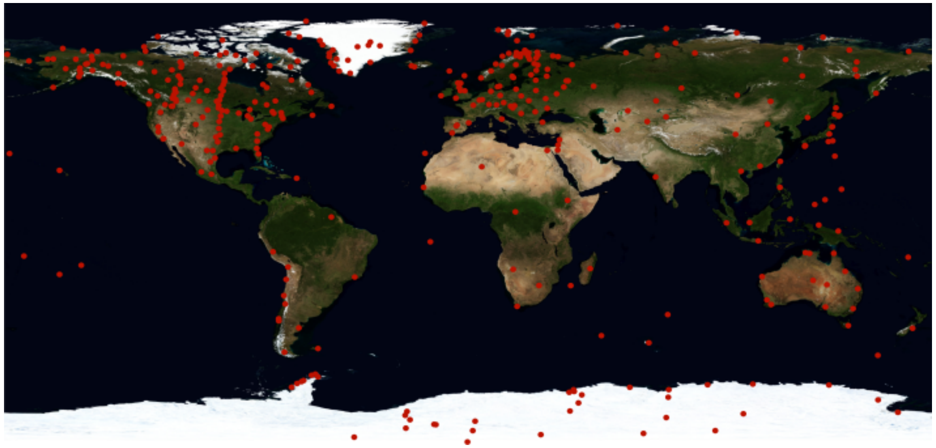
- → Continuously running assimilative models
- → Sun-to-Earth and regional modeling suites for real-time prediction and retrospective analysis
- → Use of peta-scale technologies to represent multiple spatial scales and kinetic processes

GDC has a natural, integrated Ground-Based component

→ Incoherent scatter radars, magnetometers, all sky cameras, ionosondes, Fabry-Perot observations, SuperDarn and other radars, …

GDC → Real Time "Space Weather"?

- → Gather and disseminate observations real-time?
- → "Fuse" data with global model outputs?
- → Include visualization tools that synthesize GDC, other satellite, ground-based views



SuperMAG locations

Expected Outcome → Major impact to our knowledge of I/T/Mag System and its coupling to the Sun, Space Weather effects

Geospace Dynamics Constellation will provide:

- Breakthroughs in our understanding
- Unprecedented knowledge of how upper atmospheres work on Earth and other planets
- Input for data-starved models
- Address important space weather problems